Heterodyne beatings between frequency-shifted feedback lasers

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Frequency-shifted feedback (FSF) lasers are potential candidates for long distance telemetry due to the appearance of beatings in the noise spectrum at the output of a homodyne interferometer: the frequencies of these beatings vary linearly with the path delay. In this paper we demonstrate that these beatings also occur in the heterodyne mixing of two identical, but distinct FSF lasers. This phenomenon is explained by the passive cavity model and is exploited to characterize the time-spectrum properties of FSF lasers. Consequences on telemetry with FSF lasers are presented.

Frequency shifted feedback (FSF) lasers are laser cavities with an internal frequency shifter, usually an acousto-optics modulator (AOM) [1]. Each time a photon makes a roundtrip in the cavity its frequency is shifted, resulting in an intrinsic chirp in the FSF laser field, which can be evidenced by seeding a two-beam interferometer. At the output, the spectrum of the signal measured by a fast photodiode shows beatings, whose frequencies vary linearly with the path delay of the interferometer [2]. To interpret the appearance of these beatings at the simplest level (*i.e.* neglecting the influence of the laser gain medium responsible for possible additional dynamic effects like self-pulsing), the FSF laser field has been first described by a moving comb: in the time-angular frequency (t, ω) representation the FSF laser field consists in a succession of parallel slanted lines, separated by $2\pi/\Delta$ and $2\pi/\tau_r$ along the time and angular frequency axis respectively, where τ_r is the cavity roundtrip time and Δ is the angular frequency shift per cavity roundtrip [3]. Recently it has been shown that in the general case, the time-frequency representation of the FSF laser field is not a moving comb, but rather in a more complicated 2π-periodic moving function of $(\omega\tau_r - \Delta t)$ with the same periodicities [4]. In the following this description is referred as the generalized moving comb (GMC).

The potentiality of FSF lasers for telemetry has been intensively exploited since the position of a distant target can be measured simply by recording the noise spectrum of the photodiode [5]. Interestingly these beatings also occur for path delays order of magnitude larger than the coherence time of the laser, and even larger than the photon cavity lifetime in the cavity, that is when the optical field has lost all memory [6]. This leads to the question whether these beatings are still observable between identical but distinct FSF lasers, between which no optical coherence of any kind exists.

Here we give a positive answer to this question by providing an experimental demonstration of heterodyne beatings between two FSF lasers. First we explain this result in the frame of the passive cavity model [7]. Then we use this property to characterize the time-spectrum properties of FSF lasers, in particular what determines the absolute position - the phase - of the GMC in the time-frequency plane. Note that the so-called GMC phase is not an optical phase, but denotes the phase of the 2π-periodic function of $(\omega\tau_r - \Delta t)$ describing the GMC. We report an experimental characterization of the GMC phase by using one of the lasers as a reference and we confirm experimentally that according to the passive cavity model, the phase of the GMC does not depend on the optical intracavity field but only on the time delay between both lasers and on the phase of the RF signal driving the AOM. Practical consequences for telemetry are finally discussed.

The passive cavity model is useful to explain simply the coherence properties of FSF lasers [4, 7, 8]. Recall that the electric field at the output of the passive cavity seeded by spontaneous emission satisfies the relation $E(t) = \xi(t) + Re^{i(\Delta t+\psi)}E(t-\tau_r)$ where $\xi(t)$ is the electric field of the seeding (spontaneous emission in the cavity mode), R is the reflectivity of the cavity mirror and ψ is an additional phase term characterizing the phase of the RF wave driving the AOM. Calculations lead to:

$$E(t) = \int \tilde{\xi}(\omega)\, F_{R,\Delta\tau_r}(\omega\tau_r - \Delta t - \psi)\, e^{i\omega t}\, d\omega \quad (1)$$

where $\tilde{\xi}(\omega)$ is the Fourier transform of $\xi(t)$ and $F_{R,\phi}(\theta) = \sum_{n=0}^{\infty} R^n\, e^{-in\theta}\, e^{-in(n-1)\phi/2}$ [4].

The FSF laser field can be interpreted in the time-frequency plane as the GMC, *i.e.* the product of the spectrum of the spontaneous emission, by the function $F_{R,\Delta\tau_r}$ chirping in the time-frequency plane. ψ corresponds therefore to the so-called GMC phase.

We now consider two identical FSF lasers 1 and 2 emitting the electric fields $E_1(t)$ and $E_2(t)$. Both AOMs are driven at the same angular frequency Δ and ψ_1, ψ_2 are the phases of the RF signals driving the AOMs. Without loss of generality, we choose $\psi_1 = 0$ and define $\psi = \psi_2 - \psi_1$. Assuming a relative time delay τ between the two FSF laser fields, the relative phase of the two GMCs is therefore equal to $\Delta\tau + \psi$. The mixing on the photodiode produces a photocurrent proportional to $|E_1(t) + E_2(t+\tau)|^2$. The calculation is very similar to the case of a single FSF laser seeding a homodyne interferometer with time-delay τ. In particular:

$$E_1(t)E_2^*(t+\tau) = \int G(\Omega)\, e^{i\Omega(t+\tau)} \Lambda_{R^2}(\Omega\tau_r + \Delta\tau + \psi) d\Omega \quad (2)$$

with $G(\Omega) = \sum_{q=-\infty}^{\infty} R^{|q|}\eta^q \int \tilde{\xi}_1(\omega)\, \tilde{\xi}_2^*(\omega + q\Delta - \Omega)\, e^{-i\omega(q\tau_r+\tau)} d\omega$. η is given in [4]. The shape of the resulting noise spectrum is determined by the Airy function $\Lambda_{R^2}(\Omega\tau_r \pm (\Delta\tau + \psi))$, resulting from the product of the $F_{R,\Delta\tau_r}$ functions. $|\Lambda_{R^2}(\theta)| = |1/(1 - R^2 e^{-i\theta})|$ consists in a comb of Lorentzian narrow lines at positions $\theta = 2k\pi$, k integer. Therefore the noise spectrum of the mixing of two identical FSF lasers shows beatings located at RF angular frequencies $\Omega = 2k\pi/\tau_r \pm \frac{\Delta\tau+\psi}{\tau_r}$. This calculation has an important consequence: the frequencies of the beatings do not depend on ξ_1 nor ξ_2, the optical fields in the cavities, but only on the relative phase between the GMCs $\Delta\tau + \psi$. In other words the relative GMC phase can be determined by measuring the frequencies of the heterodyne beatings.

To evidence experimentally the beatings between distinct FSF lasers and characterize the GMC phase, we built two identical dye (Rh-6G) FSF lasers based on commercial linear Coherent 599 cavities. Both lasers are pumped by the same 5 W CW pump laser at 532 nm and deliver about 100 mW each. Both AOMs are driven at 40 MHz with distinct RF drivers. The resulting angular frequency shift per roundtrip is therefore $\Delta = 2 \times 2\pi \times 40$ MHz. The cavity free spectral range is $1/\tau_r$= 270 MHz. The output mirror of laser 2 is mounted on a translation stage for a fine tuning of the cavity length. The wavelengths of both lasers are set to 585 nm by angular tuning of the AOM, and precisely matched using a high resolution spectrometer. The spectral width of the lasers is about 80 GHz FWHM. The two beams overlap on a non-polarizing beamsplitter (NPBS) and the resulting signal is detected by a photodiode (PD). A digital oscilloscope performs the FFT of the signal (Fig. 1, top). When the cavity lengths of the lasers are equalized, one observes the heterodyne beatings in the noise spectrum of the photodiode. However in the absence of cavity stabilization, their positions shift on a time scale of about 100 μs. The observation of beatings between distinct FSF lasers offers the possibility of investigating the properties of the phase of the GMC by measuring the frequency of the RF beatings between the two lasers (Fig. 1, bottom). In the following we successively study the role of the intracavity optical laser field - experimented labeled by a)-, of the time delay between the two lasers -b)- and the phase of the AOM voltages -c)- (Fig. 1).

First to check the influence of the optical field on the GMC phase, we periodically interrupt the intracavity field of laser 2 by inserting a fast mechanical chopper on

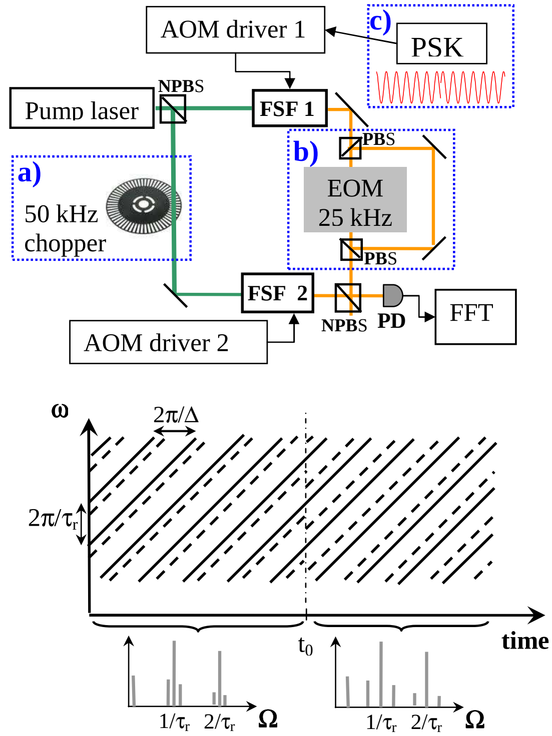

Fig. 1. Top: experimental setup showing the three different experiments -a), b) and c)- described in text. Bottom: sketch of the GMCs in the (t, ω) representation illustrating the principle of the experiments. The GMC of laser 1 (solid) is used as a reference. At t_0, a test parameter is changed here on laser 2: the optical light field, the path delay and the phase of the AOM driving signal in a), b) and c) respectively. A shift in the (RF) heterodyne beatings before and after the change of the test parameter indicates a shift in the GMC phase of laser 2 (dash).

its pump beam. The chopper period needs to be shorter than the characteristic drift time of the beatings and is set to 20 μs. Experimental results are presented on Fig. 2 a). When laser 2 is off, only laser 1 is detected by the photodiode and the usual peaks at the free spectral range (270 MHz) and a residual amplitude modulation at twice the AOM frequency (80 MHz) are recorded [8]. When laser 2 is on, one recovers the additional beatings between both FSF lasers. The beatings reappear at the same frequencies which illustrates the fact that the GMC phase of laser 2 with respect to the GMC of laser 1 is not carried by the optical field.

Then the influence of τ, the time delay between the two lasers is evidenced by inserting on the optical path of laser 1 an electro-optics modulator (EOM) rotating the polarization of the beam by 90 degrees at 25 kHz. A pair of polarizing beamsplitters (PBS) enables to commute laser beam 1 between a direct path and a loop, whose resulting path and time differences are 97 cm and $\tau = 3.2$ ns respectively (Fig. 1 top). The experimental shift in the frequency of the RF beatings is 70 MHz, in agreement with the theoretical value of $\Delta\tau/2\pi\tau_r$(Fig. 2 b).

Finally we investigate the influence of the AOM driving voltage on the GMC phase. The phase ψ of the RF signal driving AOM 2 is shifted of an angle ϕ by phase shift keying (PSK). Experimental results are plotted on Fig. 2 c) top, and show that the frequencies of the beatings change after the phase jump, which confirms the fact that the GMC phase depends on the phase of the AOM driving voltage. According to the previous calculation, for a given set of beatings with angular frequencies Ω_1 and $\Omega_2 = 2\pi/\tau_r - \Omega_1$ (with $0 < \Omega_1 < \Omega_2 < 2\pi/\tau_r$) before the phase jump, the expected positions of the beatings after the phase jump are $\Omega_1' = \Omega_1 \pm \phi/\tau_r$ and $\Omega_2' = \Omega_2 \mp \phi/\tau_r$. The uncertainty on the sign comes from the fact that the frequencies of the beatings are the same when the phase shift between both GMCs is ψ or $2\pi - \psi$. The theoretical relation between the frequencies of the beatings before and after the phase jump is plotted on Fig. 2 c) (bottom) for different values of ϕ. The excellent agreement with the experimental results confirms the theoretical predictions of the passive cavity model.

In conclusion we have observed heterodyne beatings between distinct FSF lasers, in agreement with the predictions of the passive cavity model. We have used this phenomenon to investigate the property of the phase of the GMC describing the time-spectrum properties of FSF lasers. We have checked that the GMC phase only depends on the time delay between both laser beams and on the phase of the voltage driving the AOM, but not on the optical field. This result has two important consequences for the use of FSF lasers in telemetry. First it validates the possibility of doing long range telemetry with pulsed FSF lasers since according to our results, the GMC phase is expected to be maintained from one pulse to another, similarly to [9]. Second the fact that the frequencies of the heterodyne beatings depend on the time delay between both lasers, leads to the possibility of one-way laser ranging. This work was supported in part by the Crédits d'Intervention of the CNRS and the LIPhy.

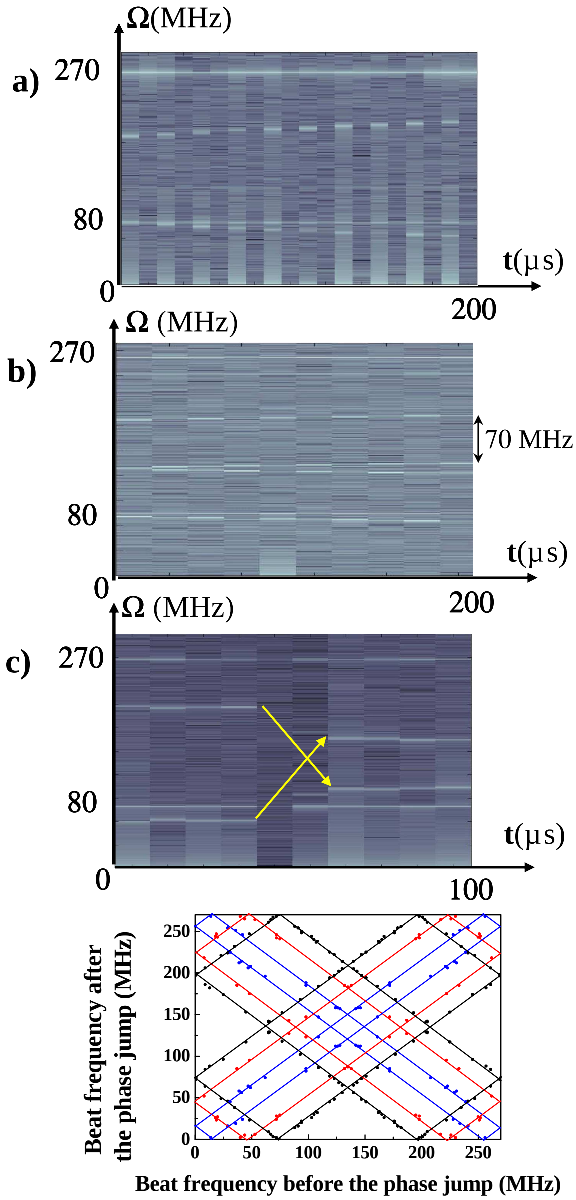

Fig. 2. Spectrum of the photodiode signal. a) The pump beam of laser 2 is chopped at 50 kHz. Spectra are sampled every 10 μs, with a 5 μs measurement time. b) The EOM switches at 25 kHz. Spectra are sampled every 20 μs, with a 5 μs measurement time. c) Top: RF spectrum before and after the AOM phase jump (PSK). Bottom: frequency of the beatings after the phase jump with respect to their value before. Blue, red and black experimental data correspond to phase jumps ϕ of 20, 60 and 100 degrees respectively. Solid lines represent the theoretical predictions.

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